REMARKS

The Office Action dated September 20, 2006, has been received and carefully considered. In this response, claim 23 has been added, and claims 13-22 have been cancelled without prejudice. Entry of the addition of claim 23, and the cancellation of claims 13-22 without prejudice is respectfully requested. Reconsideration of the outstanding rejections in the present application is also respectfully requested based on the following remarks.

I. THE ELECTION/RESTRICTION REQUIREMENT

On page 2 of the Office Action, the Examiner indicates that the election/restriction requirement as set forth in the Office Action dated June 15, 2005, has been made final.

While Applicants respectfully disagree with the position of the Examiner regarding this matter, in order to further the present application towards allowance, Applicants cancel claims 13-22 without prejudice herein.

II. THE OBVIOUSNESS REJECTION OF CLAIMS 1-7, 9, AND 10

On pages 3-5 of the Office Action, claims 1-7, 9, and 10 were rejected under 35 U.S.C. § 103(a) as being unpatentable over Steffens, Jr. (U.S. Patent No. 6,025,783) in view of

Teodorescu (U.S. Patent No. 5,986,549). This rejection is hereby respectfully traversed.

Under 35 U.S.C. § 103, the Patent Office bears the burden of establishing a prima facie case of obviousness. In re Fine, 837 F.2d 1071, 1074, 5 USPQ2d 1596, 1598 (Fed. Cir. 1988). The Patent Office can satisfy this burden only by showing some objective teaching in the prior art or that knowledge generally available to one of ordinary skill in the art would lead that individual to combine the relevant teachings of references. Id.. Obviousness cannot be established by combining the teachings of the prior art to produce the claimed invention, absent some teaching or suggestion supporting the combination. ACS Hospital Systems, Inc. v. Montefiore Hospital, 732 F.2d 1572, 1577, 221 USPQ 929, 933 (Fed. Cir. 1984). That is, under 35 U.S.C. § 103, teachings of references can be combined only if there is some suggestion or motivation to do so. Id.. However, the motivation cannot come from the applicant's invention itself. In re Oetiker, 977 F.2d 1443, 1447, 24 USPQ2d 1443, 1446 (Fed. Cir. 1992). Rather, there must be some reason, suggestion, or motivation found in the prior art whereby a person of ordinary skill in the art would make the combination. Id..

Regarding claim 1, the Examiner acknowledges that Steffens, Jr. fails to disclose a sensor that realizes a change in

inductance based upon a position of an inductance-altering activating component without using a magnet, as claimed. However, the Examiner goes on to assert that Teodorescu discloses this claim limitation, and thus the claimed invention would have been obvious in view of Steffens, Jr. and Teodorescu.

Applicants agree with the Examiner's acknowledgement of the shortcomings of Steffens, Jr., but respectfully disagree with the Examiner's assertion regarding the combination of Steffens, Jr. and Teodorescu rendering claim 1 obvious. Furthermore, Applicants respectfully submit that Steffens, Jr. fails to disclose, or even suggest, a sensor that directly interrogates the condition of the seat belt buckle by realizing a change in inductance.

Rather than simply repeating Applicants prior arguments (which Applicants still regard as valid and convincing) as to why Steffens, Jr. and Teodorescu fail to disclose, or even suggest, the invention as set forth in claim 1, Applicants believe it would be helpful to break down claim 1 into the several features recited therein. For example, claim 1 may be subdivided into the following six features:

1.) A device for recognizing the locked condition of a seat belt buckle, the device comprising:

2.) a sensor that

3.) directly interrogates the condition of the seat belt buckle

4.) by realizing a change in inductance

5.) based upon a position of an inductance-altering activating component

6.) without using a magnet.

The main focus of the present application lies in improving a sensing mechanism for interrogating a locked condition of a vehicle safety belt buckle, particularly in terms of reliability, durability, specificity, and safety aspects. Steffens, Jr. on the other hand, which is considered by the Examiner to be the closest prior art, aims at providing a wireless remote detection system which can be operated without its own energy supply at the remote site. That is, Steffens, Jr. alternatively proposes as a sensor for detecting a condition (condition sensor) a switch operated LC-circuit with a connectable inductor or a magnetic field sensor, such as a Hall effect sensor, a field-effect sensor, or a mechanical Reed contact, or a photo sensor. None of the aforementioned sensors, however, actually represents a sensor operating on an inductance basis; that is, a sensor detecting changes in inductance. Thus,

the Examiner is incorrect it his categorization of the Hall effect sensor of Steffens, Jr. as an inductance sensor (".. *responding upon the change of inductance...* "). As is well known, a Hall effect sensor operates by separating moving charge carriers in, for example, a conductor or a semiconductor by detecting changes in magnetic flux density, and not changes in inductance (e.g., see enclosed (Appendix A) hardcopies of the internet encyclopedia *Wikipedia* (wwww.wikipedia.org) referring to the items "*inductance*" and "*Hall effect sensor*"). This represents a fundamental difference between the teachings of Steffens, Jr. and the claimed invention.

Also, Steffens, Jr. fails to disclose, or even suggest, an essential claimed feature of applying the sensor in a manner to *interrogate a correct locking of a locking element directly at the locking element*. This feature is not readable from or equitable with the statement by Steffens, Jr. at column 3, lines 63 – 64: "*the switch mechanism may be any device capable of detecting movement of the buckle latch or whether the seat belt buckle tongue is received appropriately with the buckle*".

Thus, Steffens, Jr. fails to disclose, or even suggest, any of features (3), (4), (5), and (6) of claim 1. Moreover, Steffens, Jr. does not provide motivation or suggestion encouraging a person skilled in the art to search for these four

missing features (3) to (6) in the prior art. Additionally, even in the event that such a skilled person searches for these missing features and, beyond this, succeeds in finding these missing features, such a skilled person would not be able to adapt and combine these missing features with the technical teaching of Steffens, Jr. in a manner according to the present invention, as will be demonstrated below.

In particular, Teodorescu, entitled "*Position and Movement Resonant Sensor,*" has been cited by the Examiner as a teaching of feature (6) "*... by realizing a change in inductance ... without using a magnet.*" Teodorescu discloses a resonant sensor with a planar spiral winding formed as a printed circuit element constituting a "LC"-sensor which operates on a combined inductance and capacitance basis thus providing, according to Teodorescu, detection of distance and movement of conductive, non-conductive, magnetic, or non-magnetic objects (e.g., see column 7, lines 14-40), and consequently not being well adapted to solve the problem which is the focus of the presently claimed invention. Hence, Teodorescu discloses a hybrid capacitive and inductive sensor, and not a pure inductance sensor as favorable and appropriate for solving the problem which is the focus of the presently claimed invention.

Furthermore, Teodorescu would not be considered by a skilled person, namely for the following reasons:

1.) From Steffens, Jr., a person skilled in the art would neither obtain an encouragement for searching for alternatives to a Hall effect sensor nor gather any teaching or suggestion supporting a combination of the respective disclosures of Steffens, Jr. and Teodorescu.

2.) Teodorescu relates to a very different technical field (i.e., biomedicine, industry, virtual reality, multimedia; international patent classification, however, G08B 13/26 (Burglar, theft, or intruder alarms with electrical actuation by proximity of an intruder causing variation in capacitance or inductance of a circuit)), whereas a person skilled in the art would search for a solution for a device for interrogating the locked condition of a vehicle safety belt buckle.

3.) Teodorescu proposes an "LC"-sensor which is disadvantageously affected by a further parameter ("C") and other factors, like insertion of the seat belt buckle tongue, proximity of a variety of other objects whether they are conductive, non-conductive, magnetic, or non-magnetic, and consequently is not well adapted for solving the problem which is the focus of the presently claimed invention (i.e., it is

contrary to the pure inductance sensor proposed and claimed in the present application).

4.) The problem apparently solved by the teachings of Teodorescu relates to a distance and movement sensor, and not to a condition sensor precisely determining between two states, thus resulting in that the technical teaching would not be considered appropriate for being combined with the disclosure of Steffens, Jr. in order to solve a problem, which simply will not arise from the teaching of Steffens, Jr. Additionally, the problem which is the focus of the presently claimed invention (i.e., to "*...provide a clear and precise switching...*") would further distract a person skilled in the art from considering the disclosure of Teodorescu for being combined with the disclosure of Steffens, Jr.

In view of the foregoing, it is respectfully submitted that the combination of Steffens, Jr. and Teodorescu fails to disclose, or even suggest, the claimed invention as set forth in claim 1. Accordingly, it is respectfully submitted that claim 1 should be allowable over the combination of Steffens, Jr. and Teodorescu.

At this point it should be noted that new claim 23 has been added which incorporates the features of claims 1, 5, and 6. It is respectfully submitted that the claimed feature of a

differentiating circuit for the recognition of oscillation is neither shown nor suggested by any of the cited references and should consequently be appropriate for establishing patentability over prior art.

Claims 2-7, 9, and 10 are dependent upon independent claim 1. Thus, since independent claim 1 should be allowable as discussed above, claims 2-7, 9, and 10 should also be allowable at least by virtue of their dependency on independent claim 1. Moreover, these claims recite additional features which are not disclosed, or even suggested, by the cited references taken either alone or in combination.

In view of the foregoing, it is respectfully requested that the aforementioned obviousness rejection of claims 1-7, 9, and 10 be withdrawn.

III. THE OBVIOUSNESS REJECTION OF CLAIM 8

On page 6 of the Office Action, claim 8 was rejected under 35 U.S.C. § 103(a) as being unpatentable over Steffens, Jr. (U.S. Patent No. 6,025,783) in view of Teodorescu (U.S. Patent No. 5,986,549) and in further view of Todd (U.S. Patent No. 5,907,892). This rejection is hereby respectfully traversed.

It is respectfully submitted that the aforementioned obviousness rejection of claim 8 has become moot in view of the

deficiencies of the primary references Steffens, Jr. and Teodorescu as discussed above with respect to independent claim 1. That is, claim 8 is dependent upon independent claim 1 and thus inherently incorporates all of the limitations of independent claim 1. Also, the secondary reference Todd fails to disclose, or even suggest, the deficiencies of the primary references Steffens, Jr. and Teodorescu as discussed above with respect to independent claim 1. Indeed, the Examiner does not even assert such. Thus, the combination of the secondary reference Todd with the primary references Steffens, Jr. and Teodorescu also fails to disclose, or even suggest, the deficiencies of the primary references Steffens, Jr. and Teodorescu as discussed above with respect to independent claim 1. Accordingly, claim 8 should be allowable over the combination of the secondary reference Todd with the primary references Steffens, Jr. and Teodorescu at least by virtue of its dependency on independent claim 1. Moreover, claim 8 recites additional features which are not disclosed, or even suggested, by the cited references taken either alone or in combination.

In view of the foregoing, it is respectfully requested that the aforementioned obviousness rejection of claim 8 be withdrawn.

IV. THE OBVIOUSNESS REJECTION OF CLAIM 11

On pages 6-7 of the Office Action, claim 11 was rejected under 35 U.S.C. § 103(a) as being unpatentable over Todd (U.S. Patent No. 5,907,892) in view of Steffens, Jr. (U.S. Patent No. 6,025,783) and in further view of Teodorescu (U.S. Patent No. 5,986,549). This rejection is hereby respectfully traversed.

Regarding claim 11, the Examiner acknowledges that Todd and Steffens, Jr. fail to disclose a seat belt buckle having a sensor that realizes a change in inductance based upon a position of an inductance-altering activating component without using a magnet, as claimed. However, the Examiner goes on to assert that Teodorescu discloses this claim limitation, and thus the claimed invention would have been obvious in view of Todd, Steffens, Jr., and Teodorescu.

Applicant agrees with the Examiner's acknowledgement of the shortcomings of Todd and Steffens, Jr., but respectfully disagrees with the Examiner's assertion regarding the combination of Todd, Steffens, Jr., and Teodorescu rendering claim 11 obvious for at least the reasons set for above with respect to claims 1 and 8. Moreover, claim 11 recites additional features which are not disclosed, or even suggested, by the cited references taken either alone or in combination.

In view of the foregoing, it is respectfully requested that the aforementioned obviousness rejection of claim 11 be withdrawn.

V. <u>THE OBVIOUSNESS REJECTION OF CLAIM 12</u>

On page 7-8 of the Office Action, claim 12 was rejected under 35 U.S.C. § 103(a) as being unpatentable over Todd (U.S. Patent No. 5,907,892) in view of Steffens, Jr. (U.S. Patent No. 6,025,783) in further view of Teodorescu (U.S. Patent No. 5,986,549) and in further view of Husby et al. (U.S. Patent No. 5,960,523). This rejection is hereby respectfully traversed.

It is respectfully submitted that the aforementioned obviousness rejection of claim 12 has become moot in view of the deficiencies of the primary references Todd, Steffens, Jr., and Teodorescu as discussed above with respect to independent claim 11. That is, claim 12 is dependent upon independent claim 11 and thus inherently incorporates all of the limitations of independent claim 11. Also, the secondary reference Husby et al. fails to disclose, or even suggest, the deficiencies of the primary references Todd, Steffens, Jr., and Teodorescu as discussed above with respect to independent claim 11. Indeed, the Examiner does not even assert such. Thus, the combination of the secondary reference Husby et al. with the primary

references Todd, Steffens, Jr., and Teodorescu also fails to disclose, or even suggest, the deficiencies of the primary references Todd, Steffens, Jr., and Teodorescu as discussed above with respect to independent claim 11. Accordingly, claim 12 should be allowable over the combination of the secondary reference Todd with the primary references Todd, Steffens, Jr., and Teodorescu at least by virtue of its dependency on independent claim 11. Moreover, claim 12 recites additional features which are not disclosed, or even suggested, by the cited references taken either alone or in combination.

In view of the foregoing, it is respectfully requested that the aforementioned obviousness rejection of claim 12 be withdrawn.

VI. CONCLUSION

In view of the foregoing, it is respectfully submitted that the present application is in condition for allowance, and an early indication of the same is courteously solicited. The Examiner is respectfully requested to contact the undersigned by telephone at the below listed telephone number, in order to expedite resolution of any issues and to expedite passage of the present application to issue, if any comments, questions, or suggestions arise in connection with the present application.

To the extent necessary, a petition for an extension of time under 37 CFR § 1.136 is hereby made.

Please charge any shortage in fees due in connection with the filing of this paper, including extension of time fees, to Deposit Account No. 50-0206, and please credit any excess fees to the same deposit account.

Respectfully submitted,

Hunton & Williams LLP

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Date: November 20, 2006

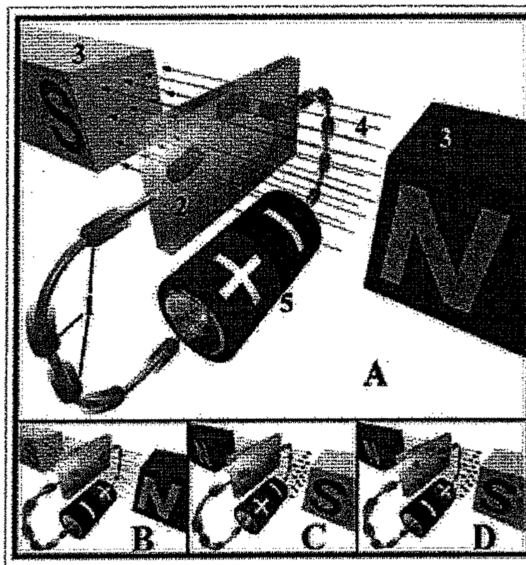
APPENDIX A

Hall effect

From Wikipedia, the free encyclopedia
(Redirected from Hall Effect Sensor)

The **Hall effect** refers to the potential difference **(Hall voltage)** on opposite sides of a thin sheet of conducting or semiconducting material in the form of a 'Hall bar' (or a van der Pauw element) through which an electric current is flowing, created by a magnetic field applied perpendicular to the Hall element. Edwin Hall discovered this effect in 1879.

The ratio of the voltage created to the product of the amount of current and the magnetic field divided by the element thickness is known as the *Hall coefficient* and is a characteristic of the material of which the element is composed.



Hall effect diagram, showing electron flow (rather than conventional current).
Legend:
1. Electrons (not conventional current!)
2. Hall element, or Hall sensor
3. Magnets
4. Magnetic field
5. Power source
Description:
In drawing "A", the Hall element takes on a negative charge at the top edge (symbolised by the blue color) and positive at the lower edge (red color). In "B" and "C", either the electric current or the magnetic field is reversed, causing the polarization to reverse. Reversing both current and magnetic field (drawing "D") causes the Hall element to again assume a negative charge at the upper edge.

Contents

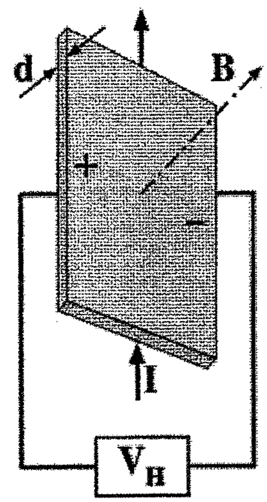
- 1 Explanation
- 2 Applications
  - 2.1 Advantages over other methods
    - 2.1.1 Ferrite toroid Hall effect current transducer
    - 2.1.2 Split ring clamp-on sensor
  - 2.2 Analog multiplication
  - 2.3 Power sensing
  - 2.4 Position and motion sensing
    - 2.4.1 Automotive ignition and fuel injection
    - 2.4.2 Wheel rotation sensing
- 3 The Corbino effect
- 4 See also
- 5 External links and references

Explanation

The Hall effect comes about due to the nature of the current flow in the conductor. Current consists of many small charge-carrying "particles" (typically electrons) which experience a force (called the Lorentz Force) when in the presence of a magnetic field. When a perpendicular magnetic field is absent, there is no Lorentz force and the charge follows an approximate 'line of sight' path. When a perpendicular magnetic field is present, the path is curved perpendicular to the magnetic field due to the Lorentz force. The result is an

asymmetric distribution of charge density across the hall element perpendicular to the 'line of sight' path the electrons would take in the absence of the magnetic field. As a result, an electric potential is generated between the two ends.

One very important feature of the Hall effect is that it differentiates between positive charges moving in one direction and negative charges moving in the opposite. The Hall effect offered the first real proof that electric currents in metals are carried by moving electrons, not by protons. The Hall effect also showed that in some substances (especially semiconductors), it is more appropriate to think of the current as positive "holes" moving rather than negative electrons.



By measuring the Hall voltage across the element, one can determine the strength of the magnetic field applied. This can be expressed as

$$V_H = \frac{IB}{ned}$$

where V_H is the voltage across the width of the plate, I is the current across the plate length, B is the magnetic flux density, d is the depth of the plate, e is the electron charge, and n is the bulk density of the carrier electrons.

So-called "Hall effect sensors" are readily available from a number of different manufacturers, and may be used in various sensors such as fluid flow sensors, power sensors, and pressure sensors.

In the presence of large magnetic field strength and low temperature, one can observe the quantum Hall effect, which is the quantization of the Hall resistance.

In ferromagnetic materials (and paramagnetic materials in a magnetic field), the Hall resistivity includes an additional contribution, known as the **Anomalous Hall Effect** (or the **Extraordinary Hall effect**), which depends directly on the magnetization of the material, and is often much larger than the ordinary Hall effect. (Note that this effect is *not* due to the contribution of the magnetization to the total magnetic field.) Although a well-recognized phenomenon, there is still debate about its origins in the various materials. The anomalous Hall effect can be either an *extrinsic* (disorder-related) effect due to spin-dependent scattering of the charge carriers, or an *intrinsic* effect which can be described in terms of the Berry phase effect in the crystal momentum space (**k**-space).

Applications

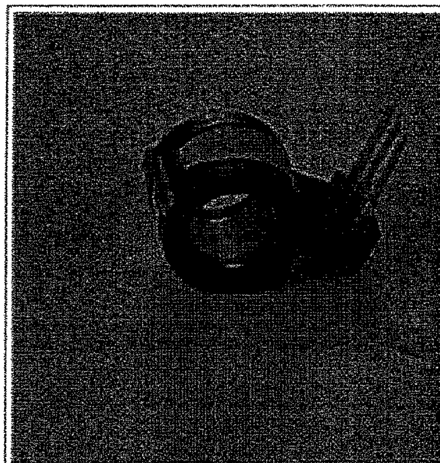
Hall effect devices produce a very low signal level and thus require amplification. While suitable for laboratory instruments, the vacuum tube amplifiers available in the first half of the 20th century were too expensive, power consuming, and unreliable for everyday applications. It was only with the development of the low cost integrated circuit that the Hall effect sensor became suitable for mass application. Many devices now sold as "Hall effect sensors" are in fact a device containing both the sensor described above and a high gain integrated circuit (IC) amplifier in a single package. Recent advances have resulted in the addition of ADC (Analog to Digital) converters and I2C (Inter-integrated circuit communication protocol) IC for direct connection to a microcontroller's I/O port being integrated into a single package, see Advanced Hall Effect

Current Transducer (http://www.raztec.co.nz/products-series3.aspx). Reed switch electrical motors using the hall effect IC is another application.

Hall probes are used to measure magnetic fields, and make use of the Hall effect.

Advantages over other methods

Hall effect devices when appropriately packaged are immune to dust, dirt, mud, and water. These characteristics make Hall effect devices better for position sensing than alternative means such as optical and electromechanical sensing.



Hall effect current sensor with internal integrated circuit amplifier. 8 mm opening. Zero current output voltage is midway between the supply voltages that maintain a 4 to 8 volt differential. Non-zero current response is proportional to the voltage supplied and is linear to 60 amperes for this particular (25 A) device.

When electrons flow through a conductor, a magnetic field is produced. Thus, it is possible to create a non-contacting current sensor. The device has three terminals. A sensor voltage is applied across two terminals and the third provides a voltage proportional to the current being sensed. This has several advantages; no additional resistance (a *shunt*, required for the most common current sensing method) need be inserted in the primary circuit. Also, the voltage present on the line to be sensed is not transmitted to the sensor, which enhances the safety of measuring equipment.

Ferrite toroid Hall effect current transducer

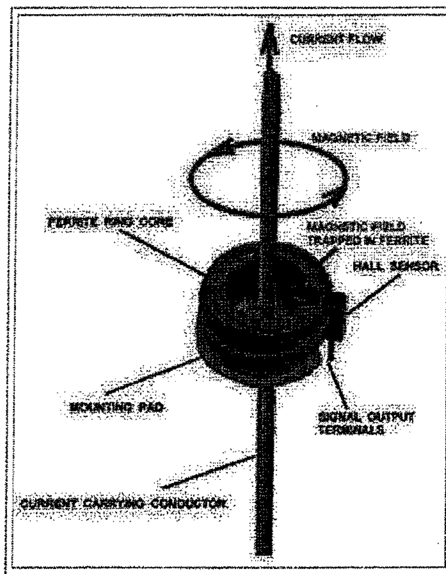
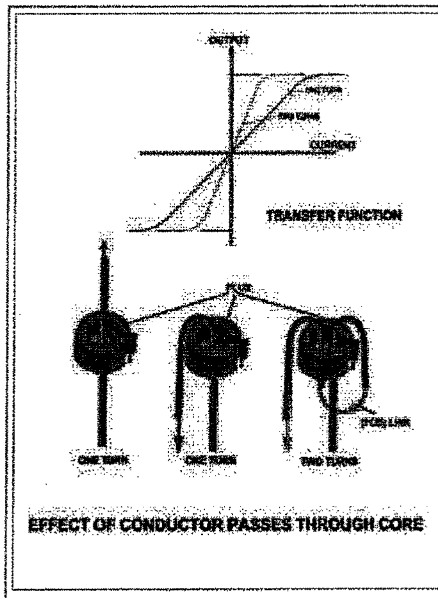


Diagram of Hall effect current transducer integrated into ferrite ring.

Hall sensors can easily detect stray magnetic fields, including that of Earth, so they work well as electronic compasses. But this also means that such stray fields can hinder accurate measurements of small magnetic fields. To solve this problem, Hall sensors are often integrated with magnetic shielding of some kind. For example, a Hall sensor integrated into a ferrite ring (as shown) can reduce stray fields by a factor of 100 or better. This configuration also provides an improvement in signal to noise ratio and drift effects of over 20 times that of a 'bare' Hall device. The range of a given feedthrough sensor may be extended upward and downward by appropriate wiring. To extend the range to lower currents, multiple turns of the current-carrying wire may be made through the opening. To extend the range to higher currents, a current divider may be used. The divider splits the current across two wires of differing widths and the thinner wire, carrying a smaller proportion of the total

current, passes through the sensor.

The principle of increasing the number of 'turns' a conductor takes around the ferrite core is well understood, each turn having the effect of 'amplifying' the current undert measurement. Often these additional turns are carried out by a staple on the PCB.



Multiple 'turns' and corresponding transfer function.

Split ring clamp-on sensor

A variation on the ring sensor uses a split sensor which is clamped onto the line enabling the device to be used in temporary test equipment. If used in a permanent installation, a split sensor allows the electrical current to be tested without dismantling the existing circuit.

Analog multiplication

The output is proportional to both the applied magnetic field and the applied sensor voltage. If the magnetic field is applied by a solenoid, the sensor output is proportional to product of the current through the solenoid and the sensor voltage. As most applications requiring computation are now performed by small (even tiny) digital computers, the remaining useful application is in power sensing, which combines current sensing with voltage sensing in a single Hall effect device.

Power sensing

By sensing the current provided to a load and using the device's applied voltage as a sensor voltage it is possible to determine the power flowing through a device. This power is (for direct current devices) the product of the current and the voltage. With appropriate refinement the devices may be applied to alternating current applications where they are capable of reading the true power produced or consumed by a device.

Position and motion sensing

Hall effect devices used in motion sensing and motion limit switches can offer enhanced reliability in extreme environments. As there are no moving parts involved within the sensor or magnet, typical life expectancy is improved compared to traditional electromechanical switches. Additionally, the sensor and magnet may be encapsulated in an appropriate protective material.

Automotive ignition and fuel injection

If the magnetic field is provided by a rotating magnet resembling a toothed gear, an output pulse will be generated each time a tooth passes the sensor. This is used in modern automotive primary distributor ignition systems, replacing the earlier "breaker" points (which were prone to wear and required periodic adjustment and replacement). Similar sensor signals are used to control multi-port sequential fuel injection systems, where each cylinder's intake runner is fed fuel from an injector consisting of a spray valve regulated by a

solenoid. The sequences are timed to match the intake valve openings and the duration of each sequence (controlled by a computer) determines the amount of fuel delivered.

Wheel rotation sensing

The sensing of wheel rotation is especially useful in anti-lock brake systems. The principles of such systems have been extended and refined to offer more than anti-skid functions, now providing extended vehicle "**handling**" enhancements.

The Corbino effect

The **Corbino effect** is a phenomenon similar to the Hall effect, but a disk-shaped metal sample is used in place of a rectangular one. A radial current through a circular disc subjected to a magnetic field perpendicular to the plane of the disk, produces a "circular" current through the disk.

See also

- Capacitor
- Elementary charge
- Frank Wilczek
- Hall effect thruster
- Nernst effect
- Nernst-Ettinghausen effect
- Quantum Hall effect
- Thermal Hall effect
- Transducer
- Van der Pauw method
- Hall probe

External links and references

Patents

- U.S. Patent 1778796 (http://patft.uspto.gov/netacgi/nph-Parser?patentnumber=1778796), P. H. Craig, *System and apparatus employing the Hall effect*

General

- Science World (wolfram.com) (http://scienceworld.wolfram.com/physics/HallEffect.html) article.
- "*The Hall Effect (http://www.eeel.nist.gov/812/effe.htm)*". nist.gov.
- Hall, Edwin, "*On a New Action of the Magnet on Electric Currents (http://www.stenomuseet.dk/skoletj/elmag/kilde9.html)*". American Journal of Mathematics vol 2 1879.
- Spin Hall Effect Detected at Room Temperature (http://physicsweb.org/articles/news/10/9/5/1)

Retrieved from "http://en.wikipedia.org/wiki/Hall_effect"

Categories: Hall effect | Condensed matter physics | Electric and magnetic fields in matter

Inductance

From Wikipedia, the free encyclopedia

Inductance (or **electric inductance**) is a measure of the amount of magnetic flux produced for a given electric current. The term was coined by Oliver Heaviside in February 1886. The SI unit of inductance is the henry (symbol: H). The symbol L is used for inductance, in honour of the physicist Heinrich Lenz.

The inductance has the following relationship:

$$L = \frac{\Phi}{i}$$

where

L is the inductance in henries,
i is the current in amperes,
Φ is the magnetic flux in webers

Strictly speaking, the quantity just defined is called *self-inductance*, because the magnetic field is created solely by the conductor that carries the current.

When a conductor is coiled upon itself N number of times around the same axis (forming a solenoid), the current required to produce a given amount of flux is reduced by a factor of N compared to a single turn of wire. Thus, the inductance of a coil of wire of N turns is given by:

$$L = \frac{\lambda}{i} = N\frac{\Phi}{i}$$

where λ is the total 'flux linkage'.

Contents

- 1 Inductance of a solenoid
- 2 Inductance of a circular loop
- 3 Inductance for any shaped loop
- 4 Properties of inductance
  - 4.1 Phasor circuit analysis and impedance
- 5 Coupled inductors
- 6 Vector field theory derivations
  - 6.1 Mutual inductance
  - 6.2 Self-inductance
- 7 Usage
- 8 See also
- 9 References

Inductance of a solenoid

The amount of magnetic flux produced by a current depends upon the permeability of the medium surrounded by the current, the area inside the coil, and the number of turns. The greater the permeability, the greater the magnetic flux generated by a given current. Certain (ferromagnetic) materials have much higher permeability than air. If a conductor (wire) is wound around such a material, the magnetic flux becomes much greater and the inductance becomes much greater than the inductance of an identical coil wound in air. The self-inductance L of such a solenoid can be calculated from

$$L = \frac{\mu_0 \mu_r N^2 A}{l} = \frac{N\Phi}{i}$$

where

μ_0 is the permeability of free space ($4\pi \times 10^{-7}$ henries per metre)
μ_r is the relative permeability of the core (dimensionless)
N is the number of turns.
A is the cross sectional area of the coil in square metres.
l is the length of the coil in metres.
$\Phi = BA$ is the flux in webers (B is the flux density, A is the area).
i is the current in amperes

This, and the inductance of more complicated shapes, can be derived from Maxwell's equations. For rigid air-core coils, inductance is a function of coil geometry and number of turns, and is independent of current. However, since the permeability of ferromagnetic materials changes with applied magnetic flux, the inductance of a coil with a ferromagnetic core will generally vary with current.

Inductance of a circular loop

The inductance of a circular conductive loop made of a circular conductor can be determined using

$$L = r\mu_0\mu_r \left(\ln\frac{8r}{a} - 2\right)$$

where

μ_0 and μ_r *are the same as above*
r is the radius of the loop
a is the radius of the conductor

Inductance for any shaped loop

Consider a current loop δS with current $i(t)$. According to Biot-Savart law, current $i(t)$ sets up a magnetic flux density at r:

$$\mathbf{B}(\mathbf{r}, t) = \frac{\mu_0 \mu_r i(t)}{4\pi} \int_{\delta S} \frac{d\mathbf{l} \times \hat{\mathbf{r}}}{r^2}$$

Now magnetic flux trough the surface S the loop encircles is:

$$\Phi(t) = \int_S \mathbf{B}(\mathbf{r},t) \cdot d\mathbf{A} = \frac{\mu_0 \mu_r i(t)}{4\pi} \int_S \int_{\delta S} \frac{d\mathbf{l} \times \hat{\mathbf{r}}}{r^2} \cdot d\mathbf{A} = Li(t)$$

From where we get the expression for inductance of the current loop:

$$L = \frac{\mu_0 \mu_r}{4\pi} \int_S \int_{\delta S} \frac{d\mathbf{l} \times \hat{\mathbf{r}}}{r^2} \cdot d\mathbf{A}$$

where

μ_0 and μ_r *are the same as above*
$d\mathbf{l}$ is the differential length vector of the current loop element
$\hat{\mathbf{r}}$ is the unit displacement vector from the current element to the field point $\boldsymbol{r}$
r is the distance from the current element to the field point $\boldsymbol{r}$
$d\mathbf{A}$ differential vector element of surface area A, with infinitesimally small magnitude and direction normal to surface S

As we see here, the geometry and material properties (if material properties are same in surface S and the material is linear) of the current loop can be expressed with single scalar quantity L.

Properties of inductance

The equation relating inductance and flux linkages can be rearranged as follows:

$$\lambda = Li$$

Taking the time derivative of both sides of the equation yields:

$$\frac{d\lambda}{dt} = L\frac{di}{dt} + i\frac{dL}{dt}$$

In most physical cases, the inductance is constant with time and so

$$\frac{d\lambda}{dt} = L\frac{di}{dt}$$

By Faraday's Law of Induction we have:

$$\frac{d\lambda}{dt} = -\mathcal{E} = v$$

where $\mathcal{E}$ is the Electromotive force (emf) and v is the induced voltage. Note that the emf is opposite to the induced voltage. Thus:

$$\frac{di}{dt} = \frac{v}{L}$$

or

$$i(t) = \frac{1}{L}\int_0^t v(\tau)d\tau + i(0)$$

These equations together state that, for a steady applied voltage v, the current changes in a linear manner, at a *rate* proportional to the applied voltage, but inversely proportionally to the inductance. Conversely, if the current through the inductor is changing at a constant rate, the induced voltage is constant.

The effect of inductance can be understood using a single loop of wire as an example. If a voltage is suddenly applied between the ends of the loop of wire, the current must change from zero to non-zero. However, a non-zero current induces a magnetic field by Ampere's law. This change in the magnetic field induces an emf that is in the opposite direction of the change in current. The strength of this emf is proportional to the change in current and the inductance. When these opposing forces are in balance, the result is a current that increases linearly with time where the rate of this change is determined by the applied voltage and the inductance.

Phasor circuit analysis and impedance

Using phasors, the equivalent impedance of an inductance is given by:

$$Z_L = V/I = jL\omega$$

where

$X_L = L\omega$ is the inductive reactance,
$\omega = 2\pi f$ is the angular frequency,
L is the inductance,
f is the frequency, and
j is the imaginary unit.

Coupled inductors

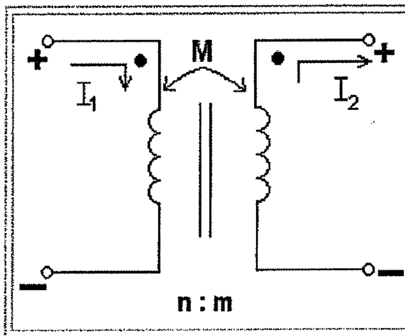
When the magnetic flux produced by an inductor links another inductor, these inductors are said to be coupled. Coupling is often undesired but in many cases, this coupling is intentional and is the basis of the transformer. When inductors are coupled, there exists a mutual inductance that relates the current in one inductor to the flux linkage in the other inductor. Thus, there are three inductances defined for coupled inductors:

L_{11} - the self inductance of inductor 1
L_{22} - the self inductance of inductor 2
$L_{12} = L_{21}$ - the mutual inductance associated with both inductors

When either side of the transformer is a tuned circuit, the amount of mutual inductance between the two windings determines the shape of the frequency response curve. Although no boundaries are defined, this is often referred to as loose-, critical-, and over-coupling. When two tuned circuits are loosely coupled through mututal inductance, the bandwidth will be narrow. As the amount of mututal inductance increases, the bandwidth continues to grow. When the mututal inductance is increased beyond a critical point, the peak in the response curve begins to drop, and the center frequency will be attenuated more strongly than its direct sidebands. This is known as overcoupling.

Vector field theory derivations

Mutual inductance



The circuit diagram representation of mutually inducting inductors.

The two vertical lines between the inductors indicate a *solid core* that the wires of the inductor are wrapped around. "n:m" shows the ratio between the number of windings of the left inductor to windings of the right inductor. This picture also shows the dot convention.

Mutual inductance is the concept that the current through one inductor can induce a voltage in another nearby inductor. It is important as the mechanism by which transformers work, but it can also cause unwanted coupling between conductors in a circuit.

The mutual inductance, M, is also a measure of the coupling between two inductors. The mutual inductance by circuit i on circuit j is given by the double integral *Neumann formula*

$$M_{ij} = \frac{\mu_0}{4\pi} \oint_{C_i} \oint_{C_j} \frac{\mathbf{ds}_i \cdot \mathbf{ds}_j}{|\mathbf{R}_{ij}|}$$

See a derivation of this equation.

The mutual inductance also has the relationship:

$$M_{21} = N_1 N_2 P_{21}$$

where

M_{21} is the mutual inductance, and the subscript specifies the relationship of the voltage induced in coil 2 to the current in coil 1.
N_1 is the number of turns in coil 1,
N_2 is the number of turns in coil 2,
P_{21} is the permeance of the space occupied by the flux.

The mutual inductance also has a relationship with the **coefficient of coupling**. The coefficient of coupling is always between 1 and 0, and is a convenient way to specify the relationship between a certain orientation of inductor with arbitrary inductance:

$$M = k\sqrt{L_1 L_2}$$

where

k is the *coefficient of coupling* and $0 \le k \le 1$,
L_1 is the inductance of the first coil, and
L_2 is the inductance of the second coil.

Once this mutual inductance factor M is determined, it can be used to predict the behavior of a circuit:

$$V = L_1 \frac{dI_1}{dt} + M \frac{dI_2}{dt}$$

where

V is the voltage across the inductor of interest,
L_1 is the inductance of the inductor of interest,
dI_1 / dt is the derivative, with respect to time, of the current through the inductor of interest,
M is the mutual inductance and
dI_2 / dt is the derivative, with respect to time, of the current through the inductor that is coupled to the first inductor.}}

When one inductor is closely coupled to another inductor through mutual inductance, such as in a transformer, the voltages, currents, and number of turns can be related in the following way:

$$V_s = V_p \frac{N_s}{N_p}$$

where
V_s is the voltage across the secondary inductor,
V_p is the voltage across the primary inductor (the one connected to a power source),
N_s is the number of turns in the secondary inductor, and
N_p is the number of turns in the primary inductor.

Conversely the current:

$$I_s = I_p \frac{N_p}{N_s}$$

where
I_s is the current through the secondary inductor,
I_p is the current through the primary inductor (the one connected to a power source),
N_s is the number of turns in the secondary inductor, and
N_p is the number of turns in the primary inductor.

Note that the power through one inductor is the same as the power through the other. Also note that these equations don't work if both transformers are forced (with power sources).

Self-inductance

Self-inductance, denoted L, is the usual inductance one talks about with an inductor. It is a special case of mutual inductance where, in the above equation, $i = j$. Thus,

$$M_{ij} = M_{jj} = L_{jj} = L_j = L = \frac{\mu_0}{4\pi} \oint_C \oint_{C'} \frac{\mathbf{ds} \cdot \mathbf{ds}'}{|\mathbf{R}|}$$

Physically, the self-inductance of a circuit represents the back-emf described by Faraday's law of induction.

Usage

The flux Φ_i through the ith circuit in a set is given by:

$$\Phi_i = \sum_j M_{ij} I_j = L_i I_i + \sum_{j \neq i} M_{ij} I_j$$

so that the induced emf, $\mathcal{E}$, of a specific circuit, i, in any given set can be given directly by:

$$E = -\frac{d\Phi_i}{dt} = -\frac{d}{dt}\left(L_i I_i + \sum_{j \neq i} M_{ij} I_j\right) = -\left(\frac{dL_i}{dt} I_i + \frac{dI_i}{dt} L_i\right) - \sum_{j \neq i}\left(\frac{dM_{ij}}{dt}\right.$$

See also

- Electromagnetic induction
- Inductor
- Dot convention
- alternating current
- electricity
- gyrator
- RLC circuit
- RL circuit
- LC circuit
- Leakage inductance
- SI electromagnetism units
- Eddy current
- Transformer

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